Beam-beam Compensation with Wires

Frank Zimmermann & Jean-Pierre Koutchouk

Thanks to
Gerard Burtin, Jackie Camas,
Fritz Caspers, Ulrich Dorda, Wolfram Fischer,
Yannis Papaphilippou, Francesco Ruggiero,
Tanaji Sen, Vladimir Shiltsev, Jorg Wenninger,…

Outline

1. **Motivation for a correction at the nominal performance**

2. **Motivation for the LHC Upgrade**

3. **Review of the studies: experiments and simulations**

1- Motivation for nominal performance

- **nominal LHC parameters are challenging & “at the edge”:**

- The machine performance is limited by the long-range beam-beam effect.

- ~20% geometric luminosity loss from crossing angle

- chaotic particle trajectories at 4-6σ due to long-range beam-beam effect

- consequence probably bad (lifetime, background to the experiments, collimation)

- requirement for a tight Xing angle control in operation:

Operational experience

Hadron Colliders:

RHIC operates with **crossing angles of +/- 0.5 mrad** due to limited BPM resolution and diurnal orbit motion. Performance of proton stores is not reproducible and frequently occurring **lifetime problems could be related to the crossing angle**, *but this is not definitely proven*. [W. Fischer]

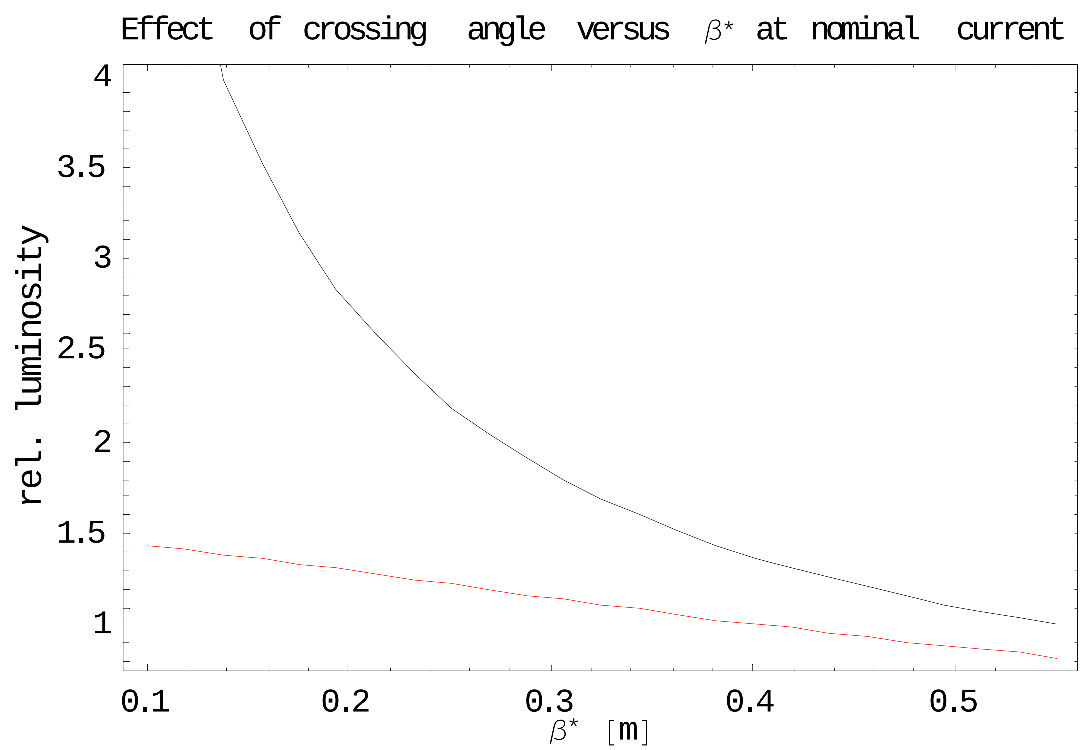
Tevatron controls crossing angle to **better than 10 μrad**, and for angles of 10-20 μrad **no lifetime degradation** is seen. [V. Shiltsev]

2- Motivation for the LHC Upgrade

- **The crossing angle shall be increased due to**
  - the reduction of β^*
  - the increased bunch current and number of bunches
  - the possibly increased interaction length (long-range)

- **The geometric luminosity loss becomes rapidly unacceptable:**

2.1 The yield from a reduced β*



Luminosity increase vs beta*:

1. no Xing angle,
2. nominal Xing and bunch length,

For both options and even more for the Q first, pushing the low-beta makes sense if simultaneously the impact of the Lumi. geometrical factor is acted upon.

2.2 Solutions for boosting the performance for the LHC Upgrade

1) **increase crossing angle BUT reduce bunch length**
   (higher-frequency rf & reduced longitudinal emittance)
   [J. Gareyte; J. Tuckmantel, HHH-20004]

2) **reduce crossing angle & apply “wire” compensation**
   [J.-P. Koutchouk]

3) **crab cavities → large crossing angles w/o luminosity loss**
   [R. Palmer, 1988; K.~Oide, K. Yokoya, 1989; KEKB 2006]

4) **collide long intense bunches with large crossing angle**
   [F. Ruggiero, F. Zimmermann, ~2002]

baseline upgrade parameters invoke shorter or longer bunches

Parameters for various LHC upgrade options compared with nominal and ultimate values						
Parameter	Symbol	Nominal	Ultimate	Shorter bunches		Longer bunches
number of bunches	n_b	2808	2808	4680	7020	936
protons per bunch	N_b (10^{11})	1.15	1.7	1.7		6.0
bunch spacing	Δt_{sep} (ns)	25	25	15	10	75
average current	I (A)	0.58	0.86	1.43	2.15	1.0
longitudinal profile	–	Gaussian	Gaussian	Gaussian		uniform
rms bunch length	σ_z (cm)	7.55	7.55	3.78		14.4
beta at IP1 and IP5	β^* (m)	0.55	0.5	0.25		0.25
crossing angle	θ_c (μrad)	285	315	445		430
Piwinski parameter	$\theta_c\sigma_z/(\sigma^*2)$	0.64	0.75	0.75		2.8
luminosity	L $(10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1})$	1.0	2.3	7.7	11.5	8.9
events per crossing	–	19	44	88		510

F. Ruggiero, F. Zimmermann, HHH-2004

beam-beam compensation with wires or crab cavities would change the optimum beam parameters and could greatly affect the IR layout

2.3 minimum crossing angle from LR b-b

$$\theta_c \cong \sqrt{\frac{\varepsilon}{\beta^*}}\left(6.5+3\sqrt{\frac{k_{par}}{2x32}\frac{N_b}{10^{11}}\frac{3.75\mu m}{\gamma\varepsilon}}\right)$$

"Irwin scaling" coefficient from simulation

note: there is a threshold - a few LR encounters may have no effect! (2nd PRST-AB article with Yannis Papaphilippou)

crossing angle with wire compensator

$$\theta_c \cong 9.5 \rightarrow 8\sqrt{\frac{\varepsilon}{\beta^*}}$$

need dynamic aperture of 5-6 σ & wire compensation not efficient within 2 σ from the beam center

<u>independent of beam current</u>

Quad requirements: nominal beam current

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case14-1: Nb3Sn triplet at 23m, otherwise nominal conditions

β_{IP} 0.25 m	N_{bunch} $1.15\ 10^{11}$ p	k_b 2808	Xing HV	$\mathcal{L}/\mathcal{L}_0$ 1.54
$\ell_{IP\to Q1}$ 23. m	$<\ell_Q>$ 5.5 m	ℓ_{LR} 54. m	31. – 0.12 Ic 44. – 0.35 Ic	
Gradient 234. T / m	coil oversize 1.	ϕ_{inner} coil 92.4 mm	B_{max} 10.8 T	power dens 0.982 mW / g
Efficiency :	NbTi 126. %	NbTiTa 117. %	Nb3Sn 82.7 %	
β_{max} 9373.1 m	K2[Q'] 84.9 %	K2[Q', Q''] 111. %	coef.b6 10.3	coef.b10 46.7
ϕ_{beam} 83.7 mm	$\sigma_{\beta max}$ 2.17 mm	$a_{disp, max}$ 4.58 mm	beam sep Q2 20.4 mm	θ_c 421. μrad

Quad requirements: ultimate beam current

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case14-2a: Nb3Sn triplet at 23m, ultimate bunch current, bunch spacing halfed
Papaphilippou/Zimmermann angle scaling with current

β_{IP} 0.25 m	N_{bunch} $1.7\ 10^{11}$ p	k_b 5616	Xing HV	$\mathcal{L}/\mathcal{L}_0$ 5.83
$\ell_{IP\to Q1}$ 23. m	$<\ell_Q>$ 5.5 m	ℓ_{LR} 54. m	31. − 0.12 lc 44. − 0.35 lc	
Gradient 234. T / m	coil oversize 1.	ϕ_{inner} coil 98.4 mm	B_{max} 11.5 T	power dens 4.29 mW / g
Efficiency :	NbTi 134. %	NbTiTa 125. %	Nb3Sn 88. %	
β_{max} 9373.1 m	K2[Q'] 84.9 %	K2[Q', Q''] 111. %	coef.b6 10.3	coef.b10 46.7
ϕ_{beam} 89.7 mm	$\sigma_{\beta max}$ 2.17 mm	$a_{disp,max}$ 5.05 mm	beam sep Q2 24.9 mm	θ_c 515. μrad

Quad requirements: ultimate beam current with BBLR

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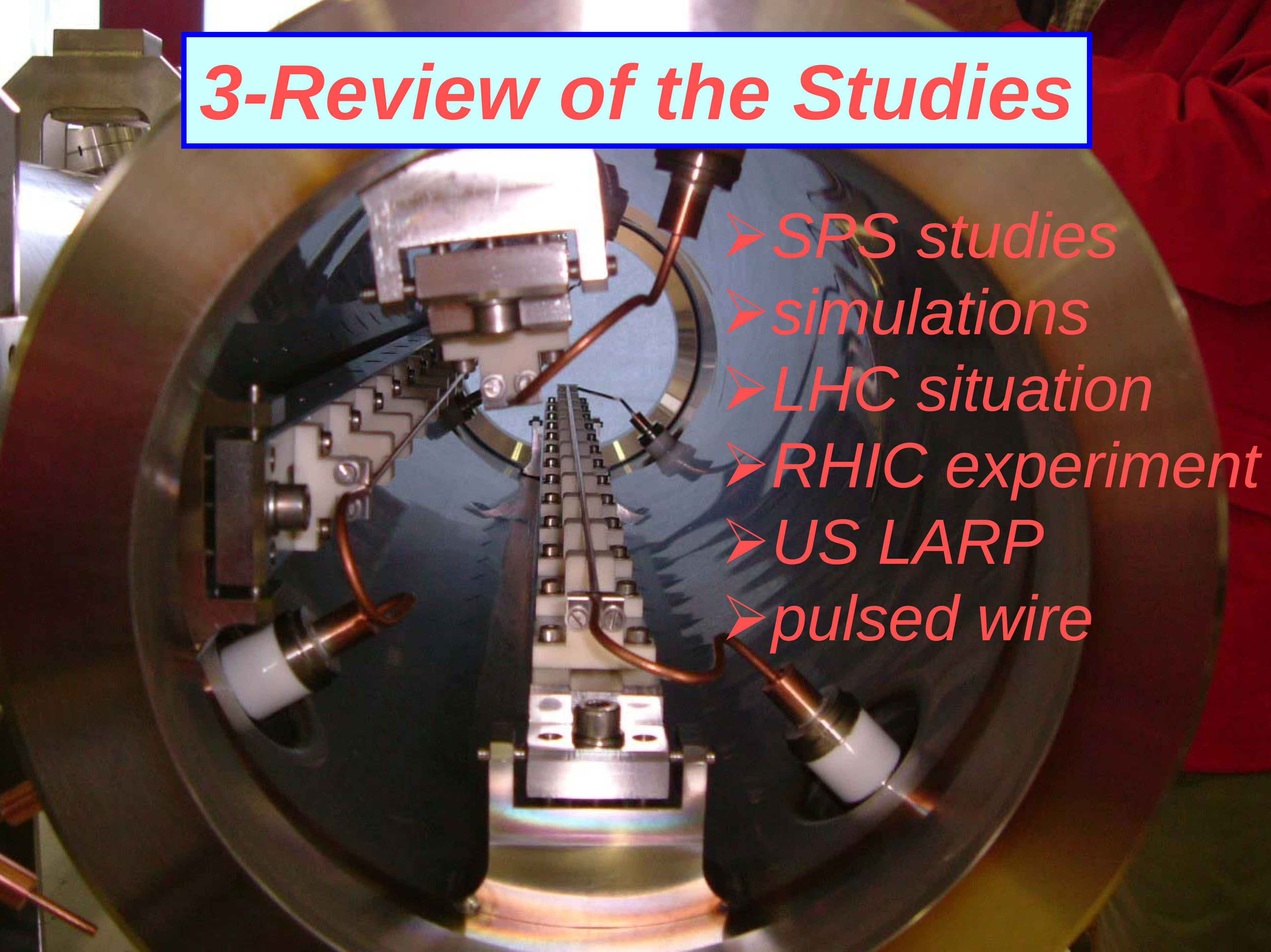
case14-3: Nb3Sn triplet at 23m, bunch charge doubled, HH Xing with BBLR

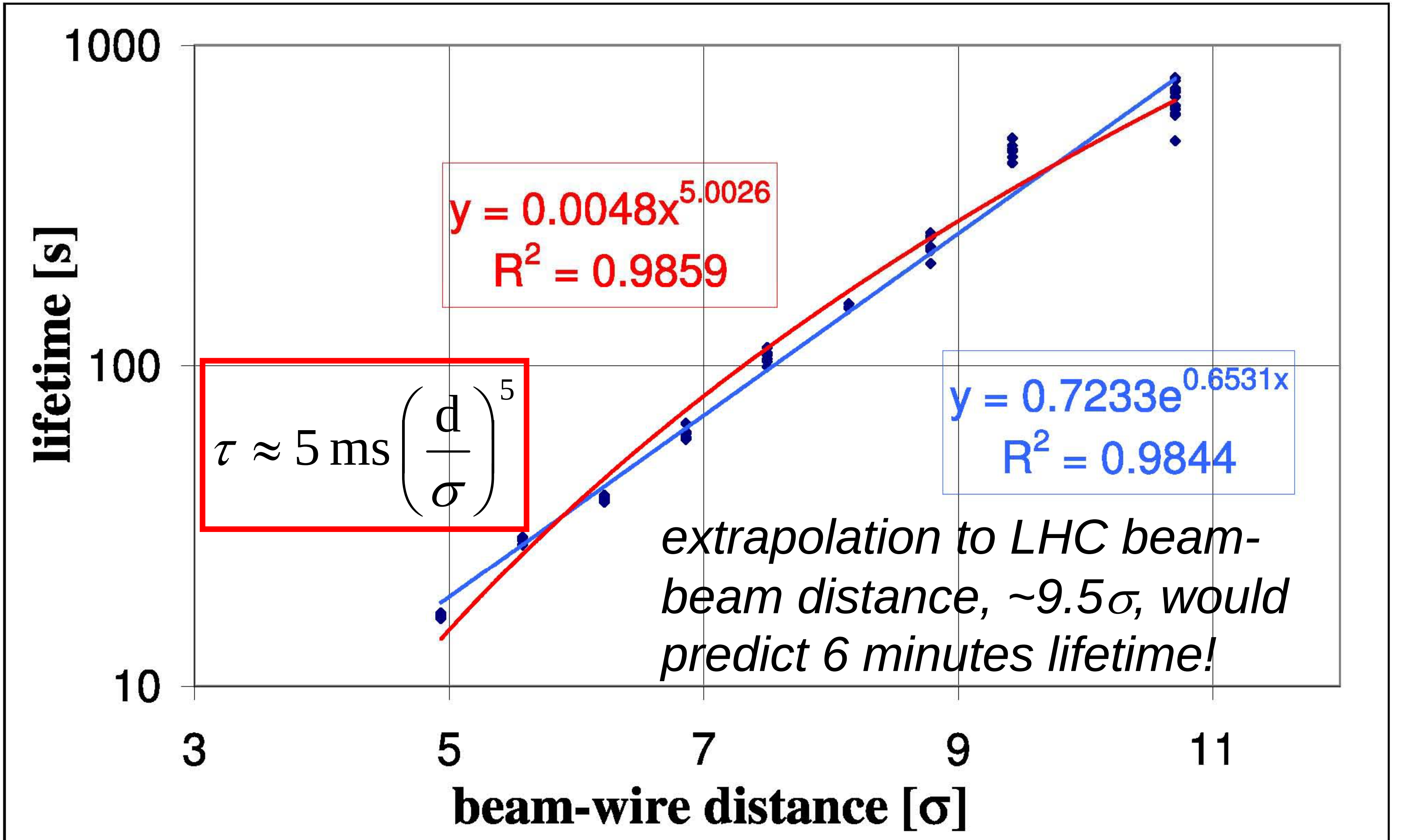
β_{IP} 0.25 m	N_{bunch} $2.3\ 10^{11}$ p	k_b 2808	Xing BBLR	$\mathcal{L}/\mathcal{L}_0$ 6.14
$\ell_{IP\to Q1}$ 23. m	$<\ell_Q>$ 5.5 m	ℓ_{LR} 54. m	31. − 0.12 lc 44. − 0.35 lc	
Gradient 234. T / m	coil oversize 1.	ϕ_{inner} coil 88.4 mm	B_{max} 10.4 T	power dens 3.91 mW / g
Efficiency :	NbTi 121. %	NbTiTa 112. %	Nb3Sn 79. %	
β_{max} 9373.1 m	K2[Q'] 84.9 %	K2[Q', Q''] 111. %	coef.b6 10.3	coef.b10 46.7
ϕ_{beam} 79.7 mm	$\sigma_{\beta max}$ 2.17 mm	$a_{disp,max}$ 2.48 mm	beam sep Q2 20.5 mm	θ_c 423. μrad

3-Review of the Studies

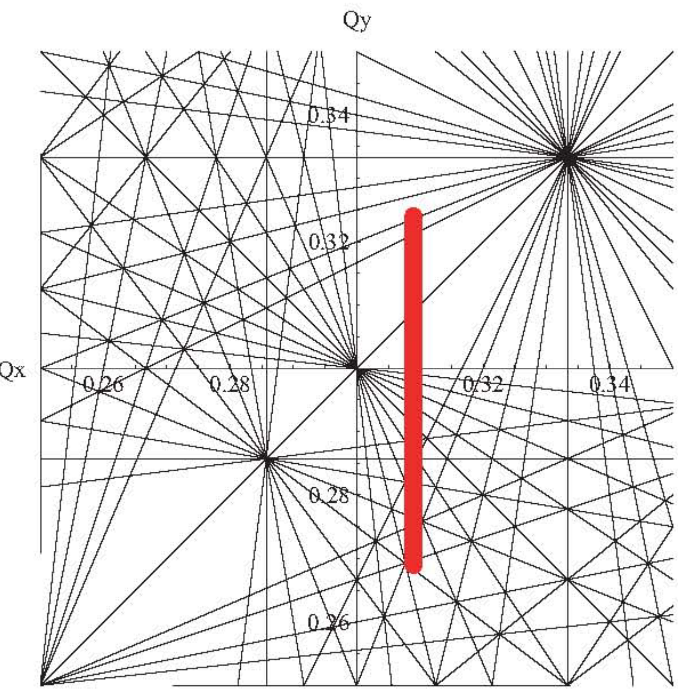


- SPS studies
- simulations
- LHC situation
- RHIC experiment
- US LARP
- pulsed wire

3.1 SPS experiment:
1 wire models LHC long-range interaction

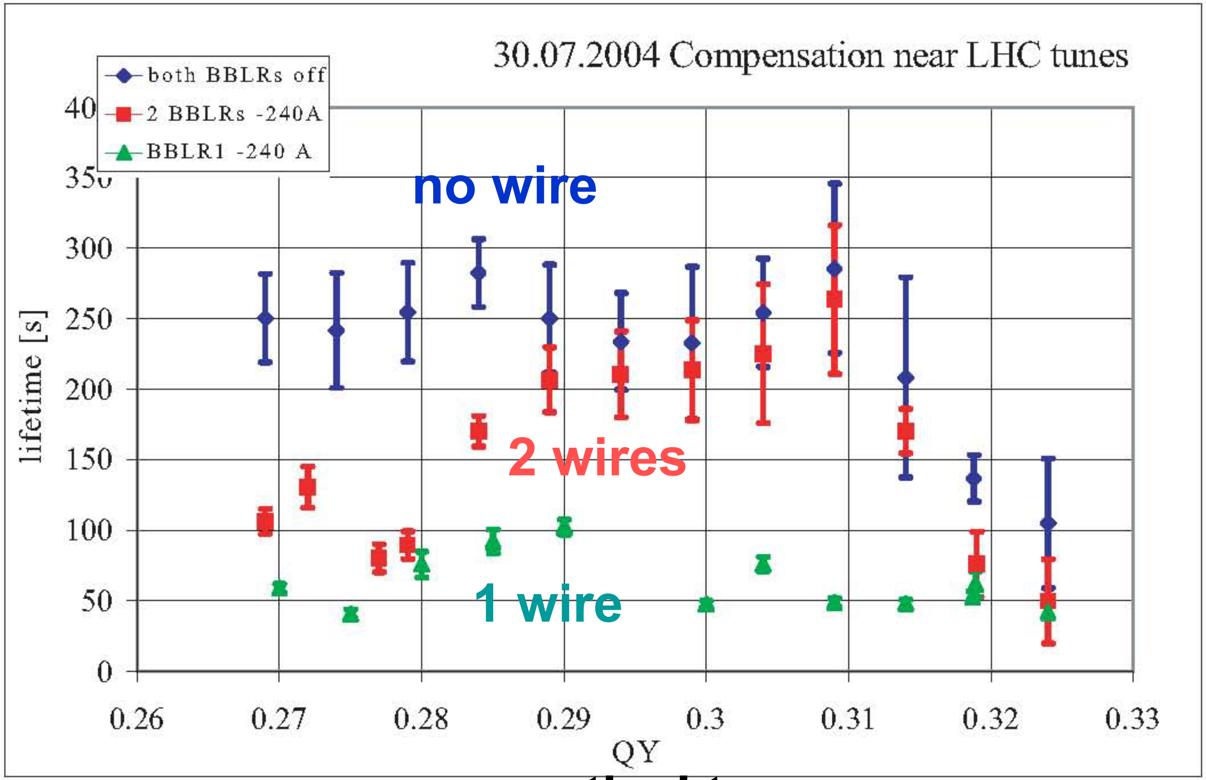


SPS experiment:
two wires model beam-beam compensation



Q_x=0.31

beam lifetime



vertical tune

lifetime is recovered over a large tune range, except for Qy<0.285

3.2 New Simulation Tool: BBTrack

Purpose of the code:
Detailed weak-strong simulations of long-range and head-on beam-beam interactions and wire compensation.

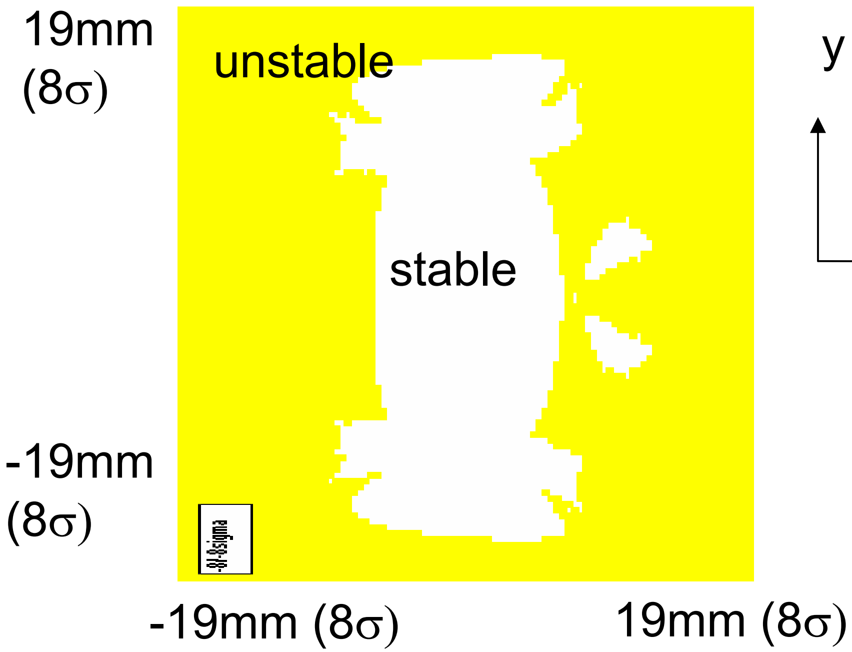
Author: Ulrich Dorda, CERN

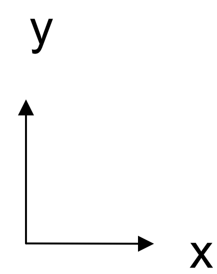
Programming language: FORTRAN90

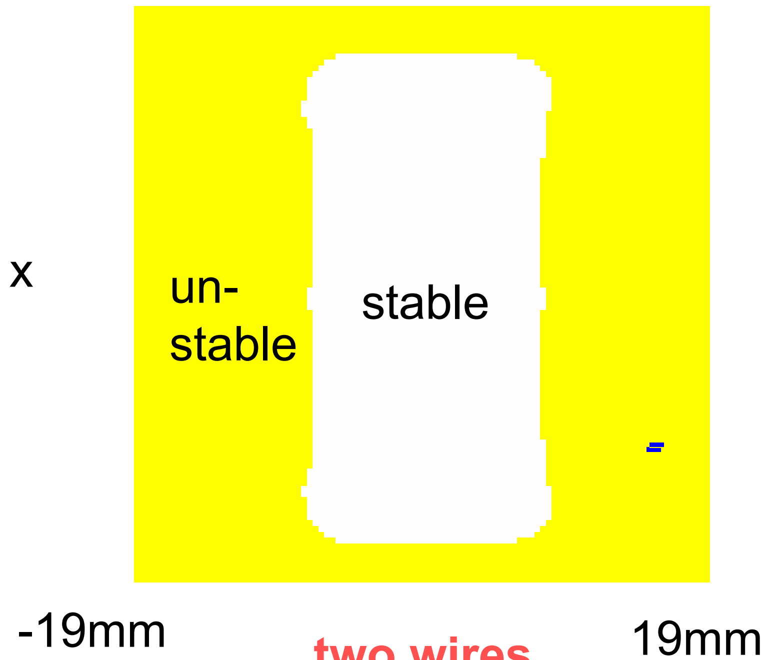
Homepage : *http://ab-abp-bbtrack.web.cern.ch/ab-abp-bbtrack/*

Other codes used:
WSDIFF (F. Zimmermann, CERN)
http://care-hhh.web.cern.ch/CARE-HHH/Simulation Codes/Beam-Beam/wsdiff.htm
BBSIM (T. Sen, FNAL)
http://waldo.fnal.gov/~tsen/BBCODE/public

simulated stability region in x-y plane with1 & 2 SPS wires

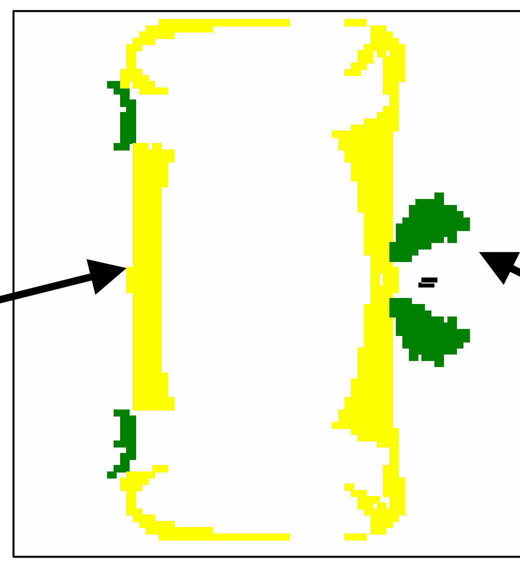






one wire

two wires

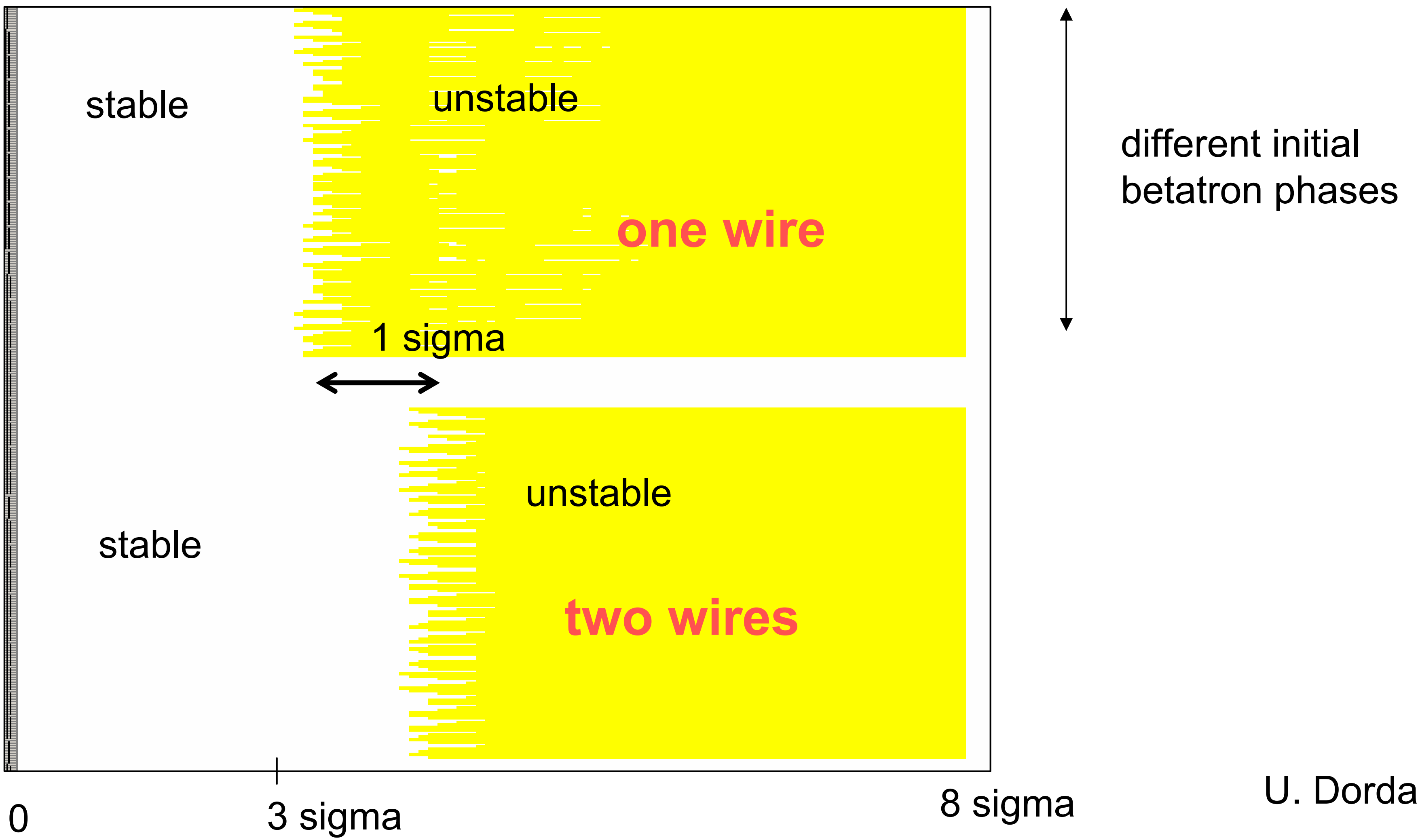


Yellow: stable with two wires & unstable with one

Green: unstable with one wire & stable with two

U. Dorda

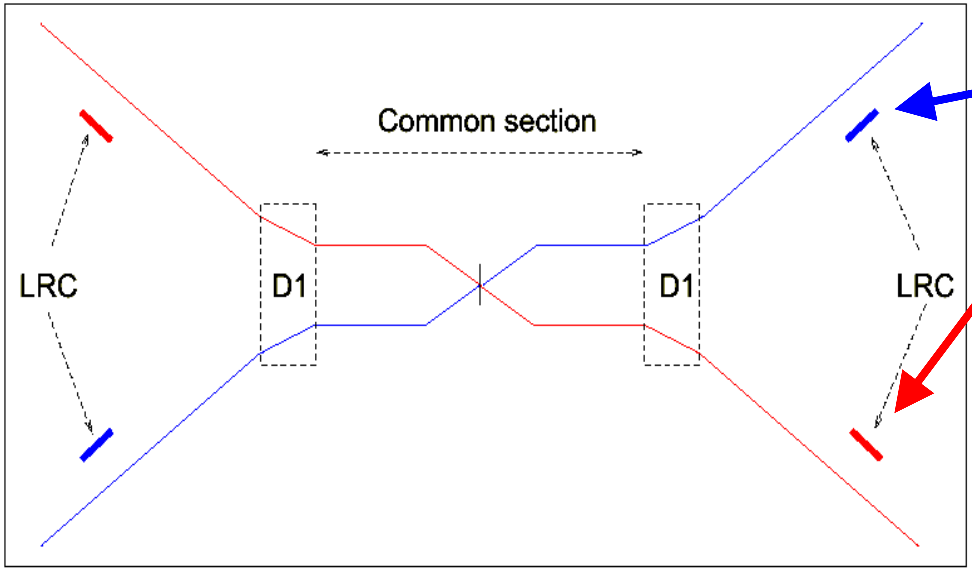
simulation of wire compensation for the SPS experiment



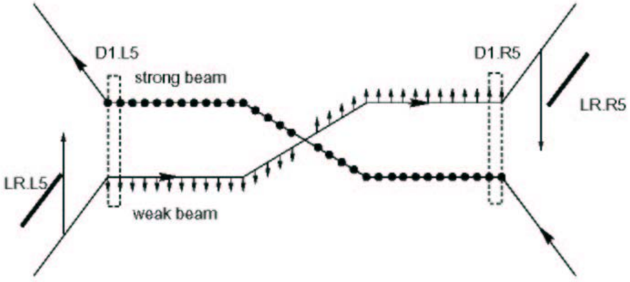
U. Dorda

3.3 Long-Range Beam-Beam Compensation for the LHC

- To correct **all** non-linear effects correction must be **local**
- Layout: 41 m upstream of D2, both sides of IP1/IP5



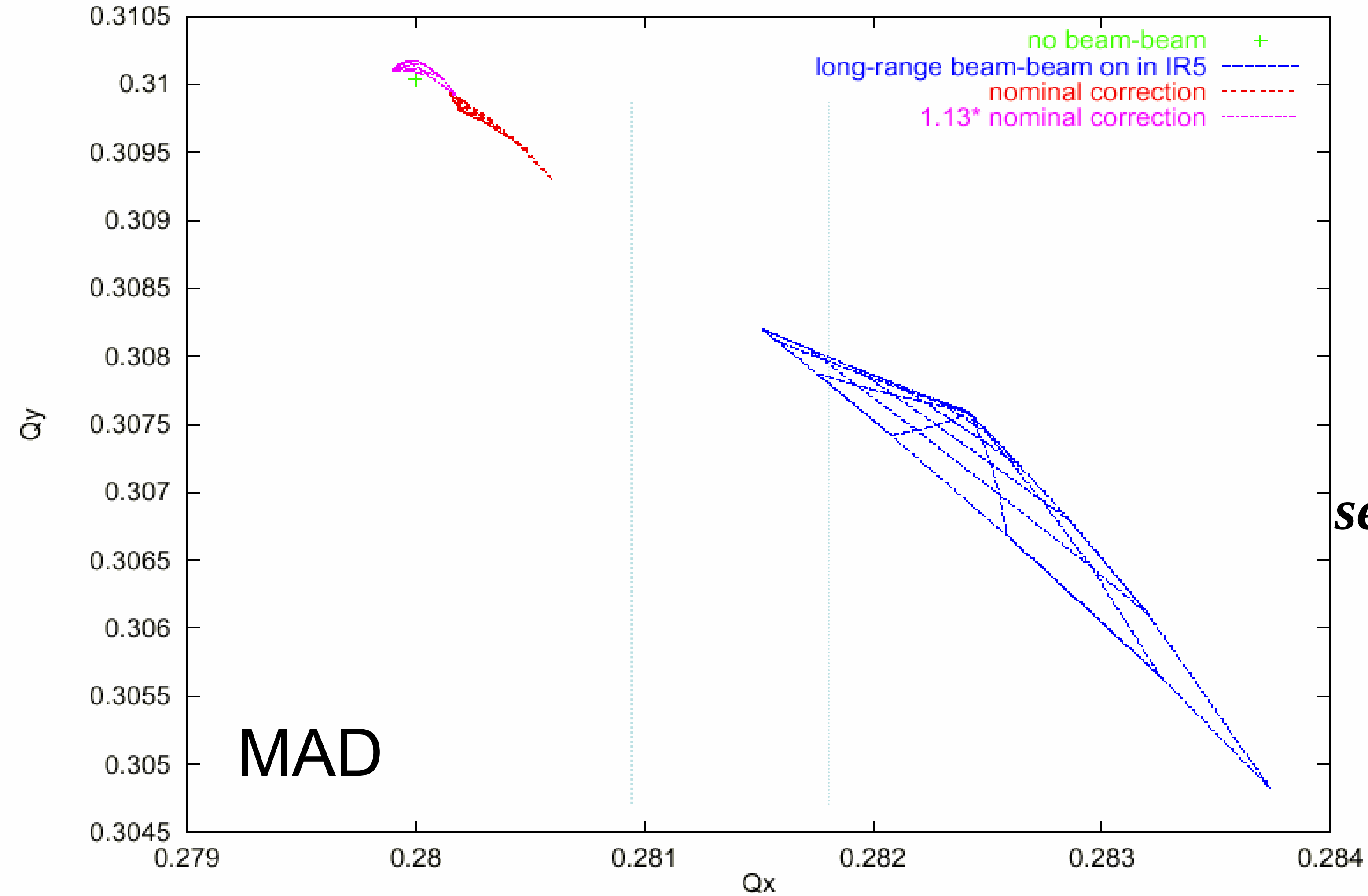
current-carrying wires



Phase difference between BBLRC & average LR collision is 2.6°

(Jean-Pierre Koutchouk)

simulated LHC tune footprint with & w/o wire correction



•.16σ

•.005σ

•.016σ

Beam separation at IP

(Jean-Pierre Koutchouk, LHC Project Note 223, 2000)

CERN
CH-1211 Geneva 23
Switzerland

the
Large
Hadron
Collider
project

LHC Project Document No. **LHC-BBC-EC-0001**
EDMS Document No. **503722**
Engineering Change requested by (Name & Div./Grp.) : **C.Fischer AB/BDI**

Date: 2004-10-27

Engineering Change Order – Class I

RESERVATIONS FOR BEAM-BEAM COMPENSATORS IN IR1 AND IR5

Brief description of the proposed change(s) :

Reservations on the vacuum chamber in IR1 and IR5 for beam-beam compensator monitors.
We propose to include these modifications in the next v.6.5 machine layout version.

Equipment concerned :	*Drawings concerned :*	*Documents concerned :*
BBC	**LHCLSX—0001** **LHCLSX—0002** **LHCLSX—0009** **LHCLSX—0010**	

PE in charge of the item :	*PE in charge of parent item in PBS :*
J.P. Koutchouk AT/MAS	**C. Rathjen AT/VAC**

Decision of the Project Engineer :	*Decision of the PLO for Class I changes :*
☐ Rejected. ☐ Accepted by Project Engineer, no impact on other items. *Actions identified by Project Engineer* ☑ Accepted by Project Engineer, but impact on other items. *Comments from other Project Engineers required* *Final decision & actions by Project Management*	☐ Not requested. ☐ Rejected. ☑ Accepted by the Project Leader Office. *Actions identified by Project Leader Office*
Date of Approval : 2004-10-27	***Date of Approval :*** 2004-10-27

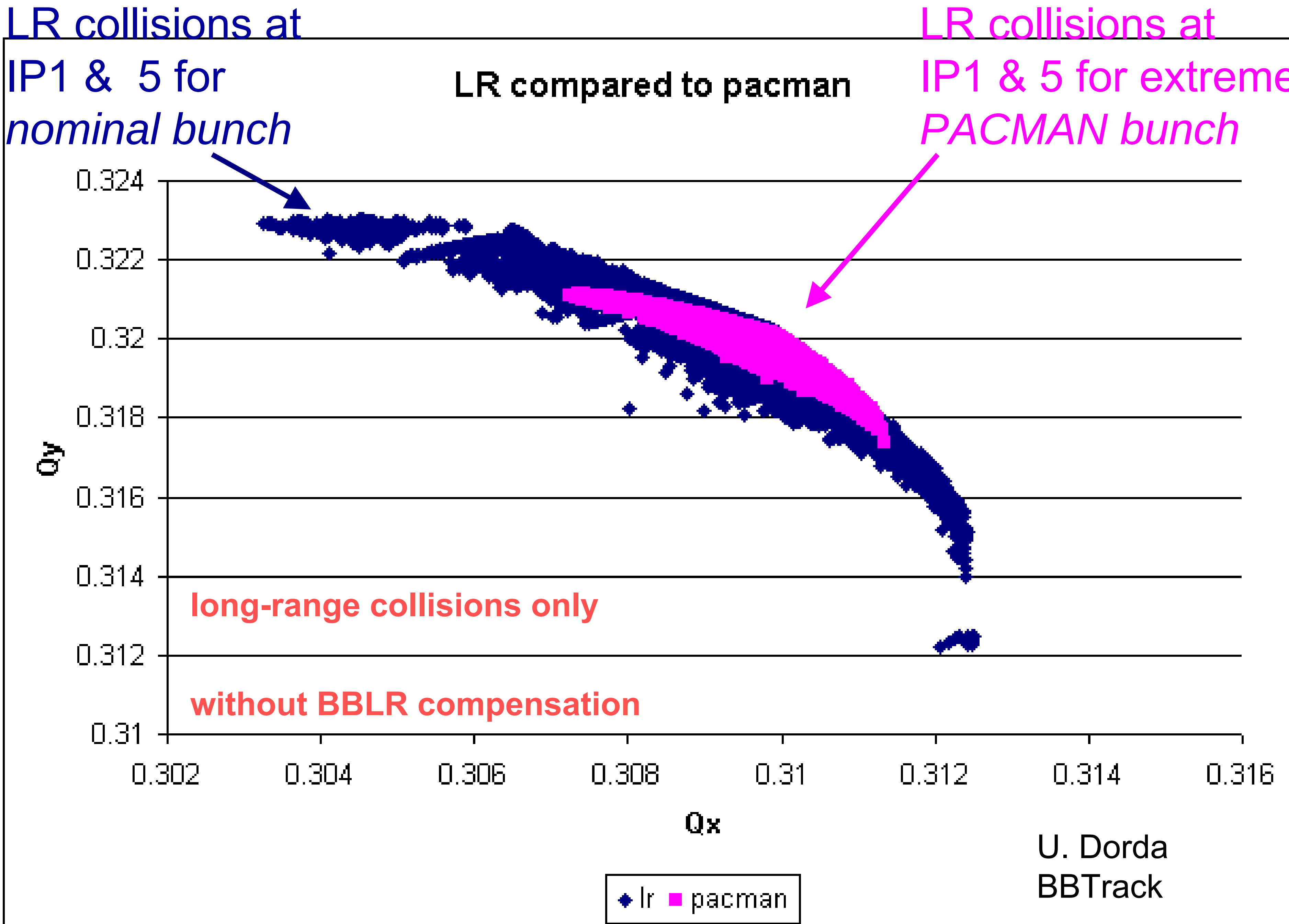
Actions to be undertaken :

Modify the drawings and Equipment codes concerned to reflect the changes described in this ECO.

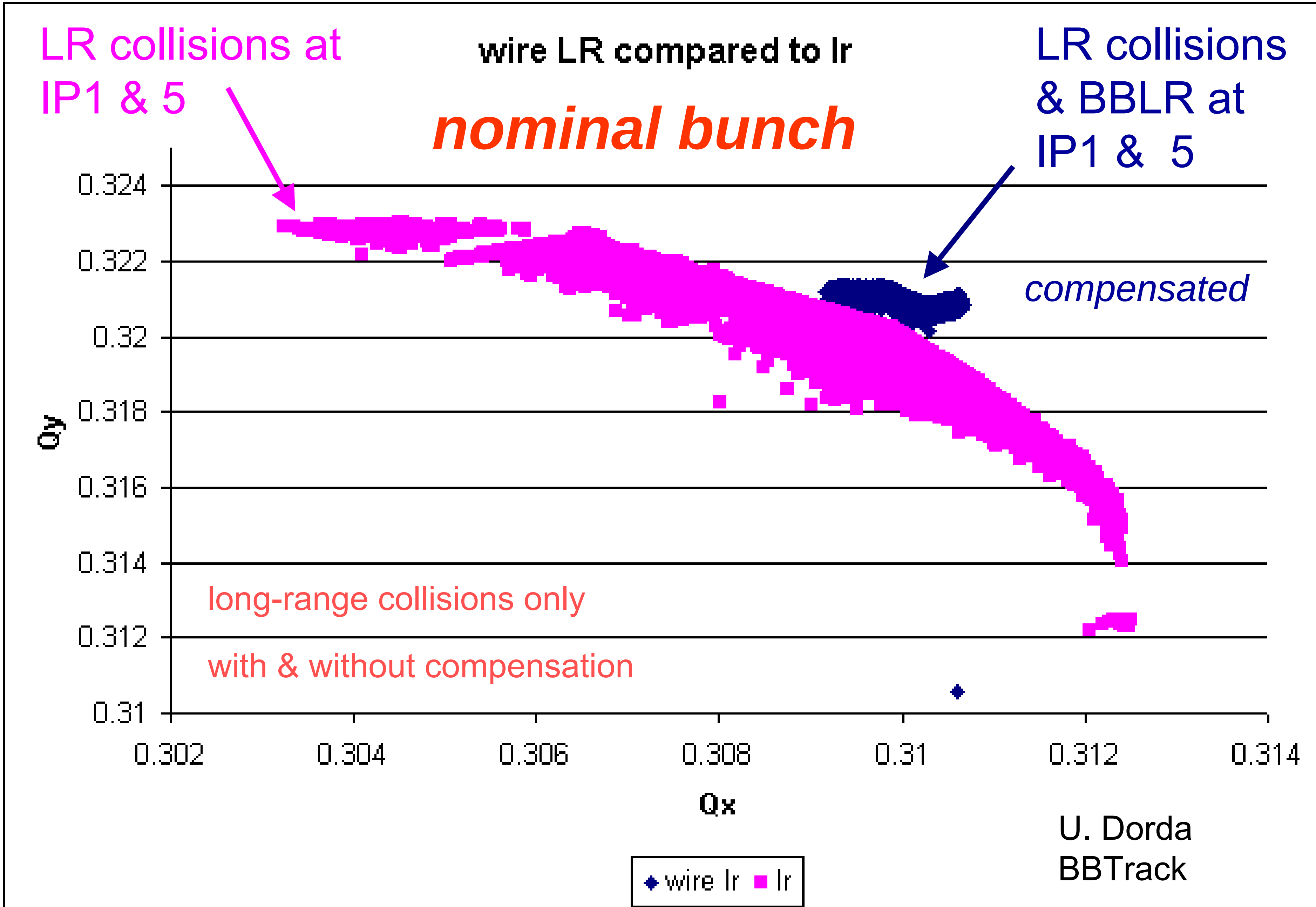
Date of Completion : 2004-10-27	***Visa of QA Officer :***

Note : when approved, an ***Engineering Change Request*** *becomes an* ***Engineering Change Order/Notification.***

for future wire beam-beam compensators
- "BBLRs" -,
3-m long sections have been reserved in LHC at 104.93 m (center position) on either side of IP1 & IP5



tune footprints for starting amplitudes up to 6σ in x and y



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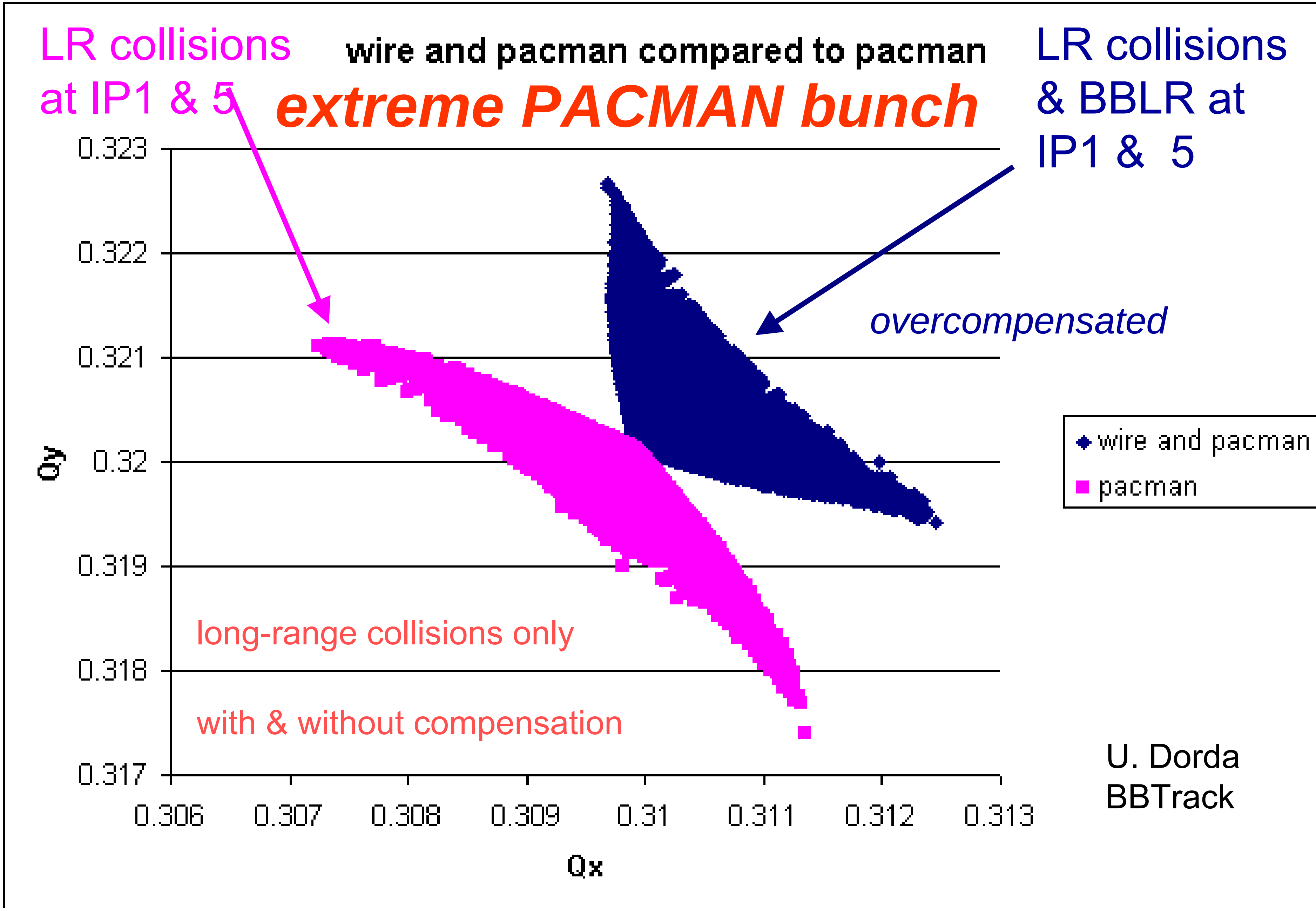
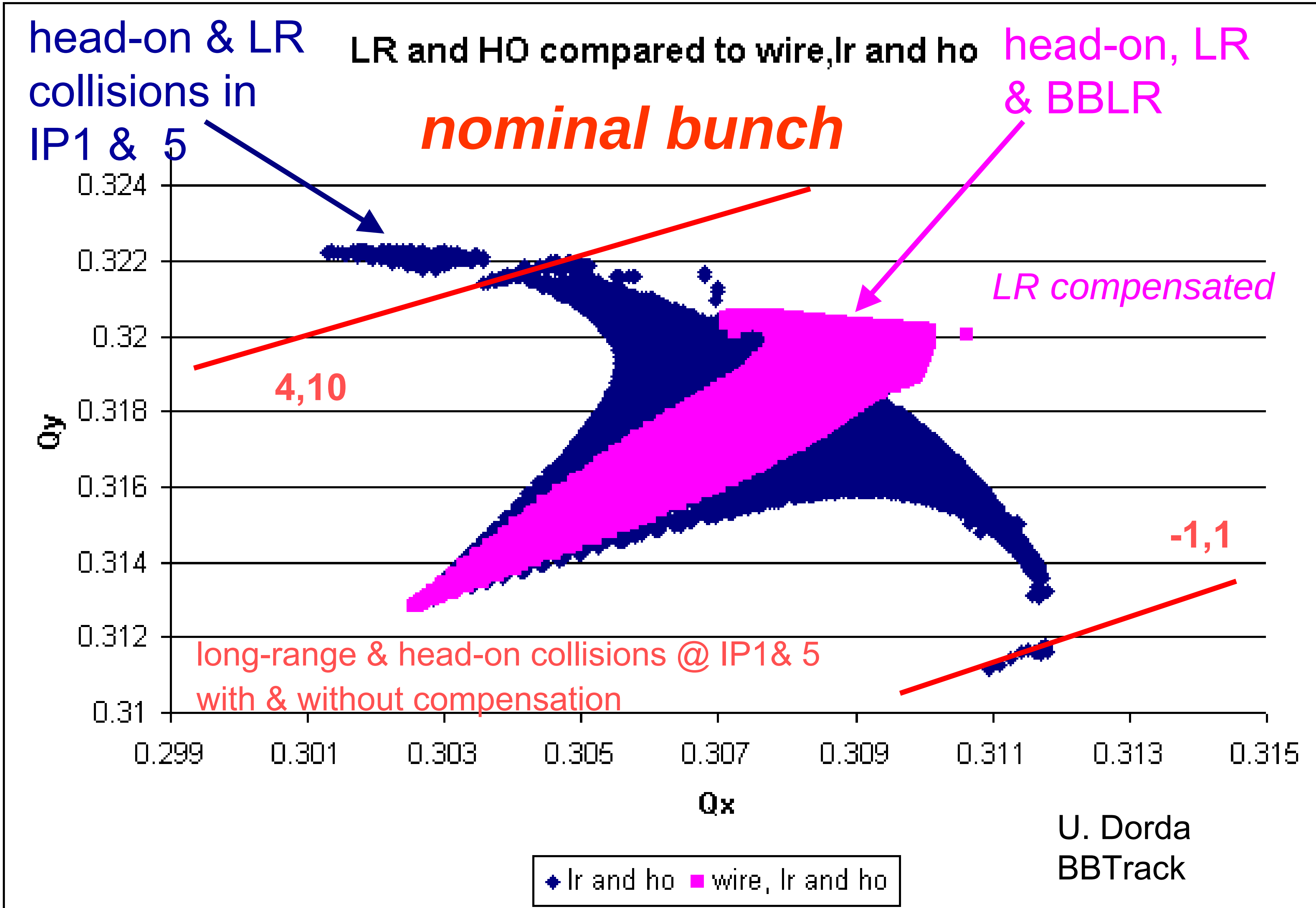
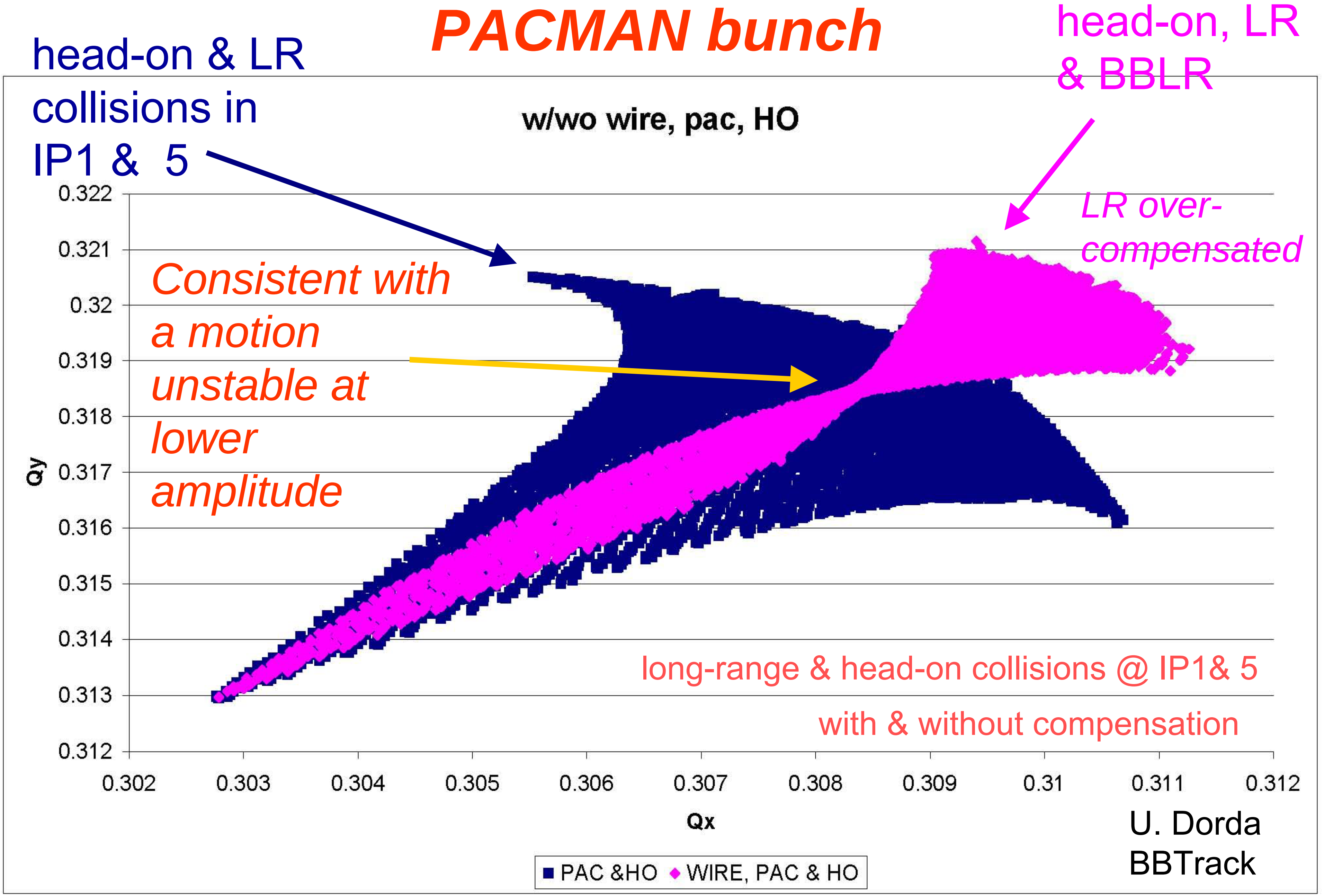


tune footprints for starting amplitudes up to 6σ in x and y



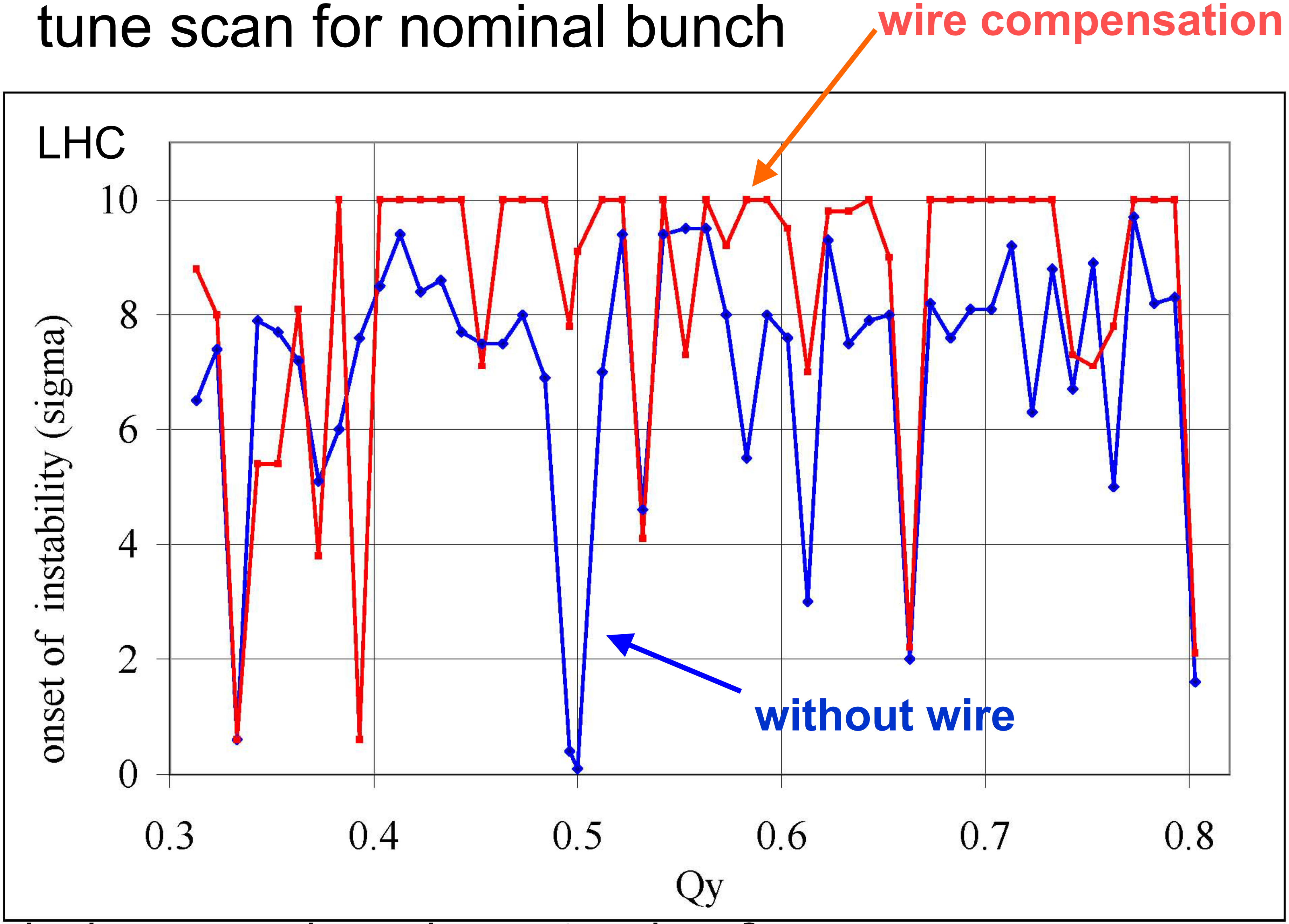
tune footprints for starting amplitudes up to 6σ in x and y

PACMAN bunch



tune footprints for starting amplitudes up to 6σ in x and y

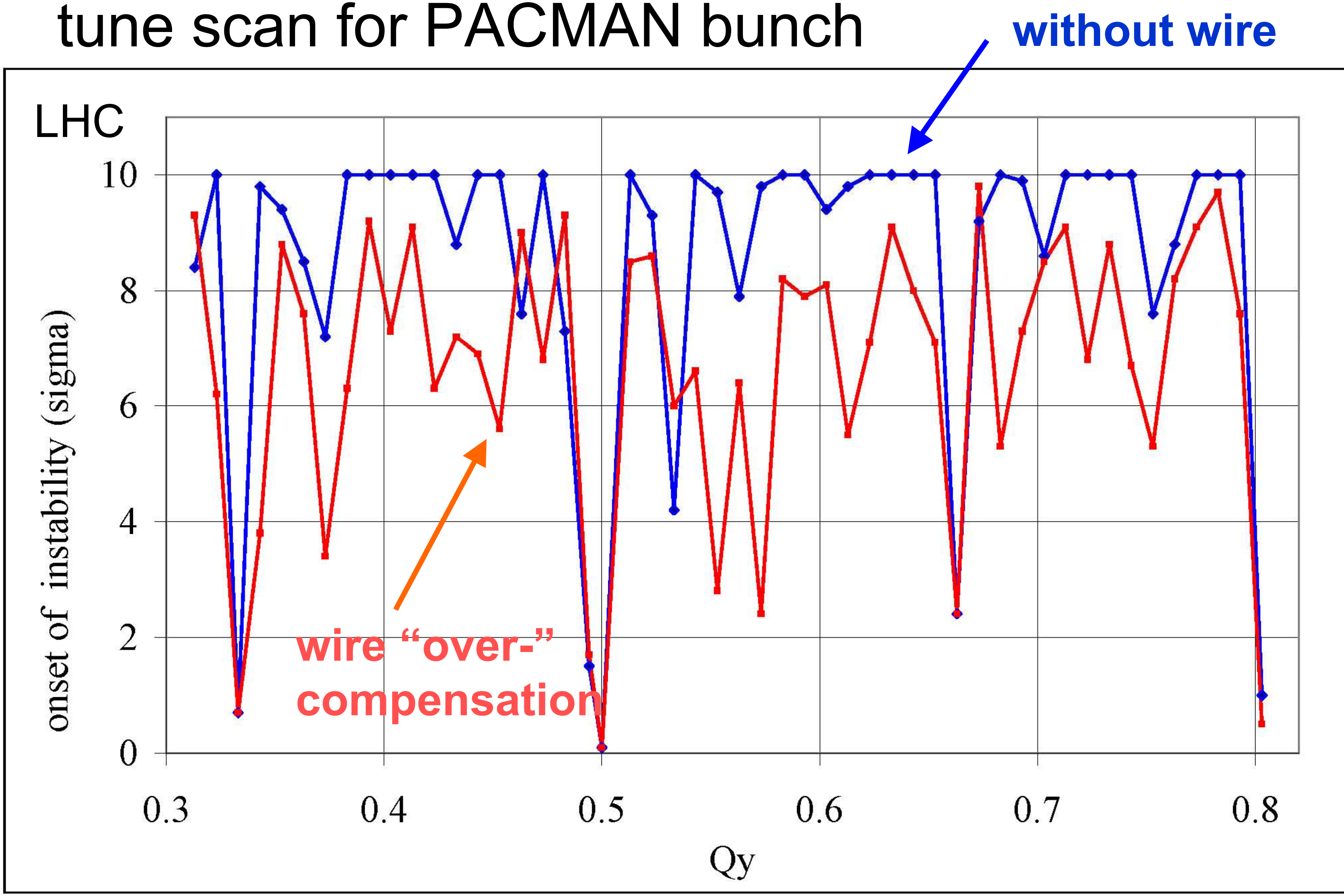
tune scan for nominal bunch



wire increases dynamic aperture by ~2σ

U. Dorda, BBTrack

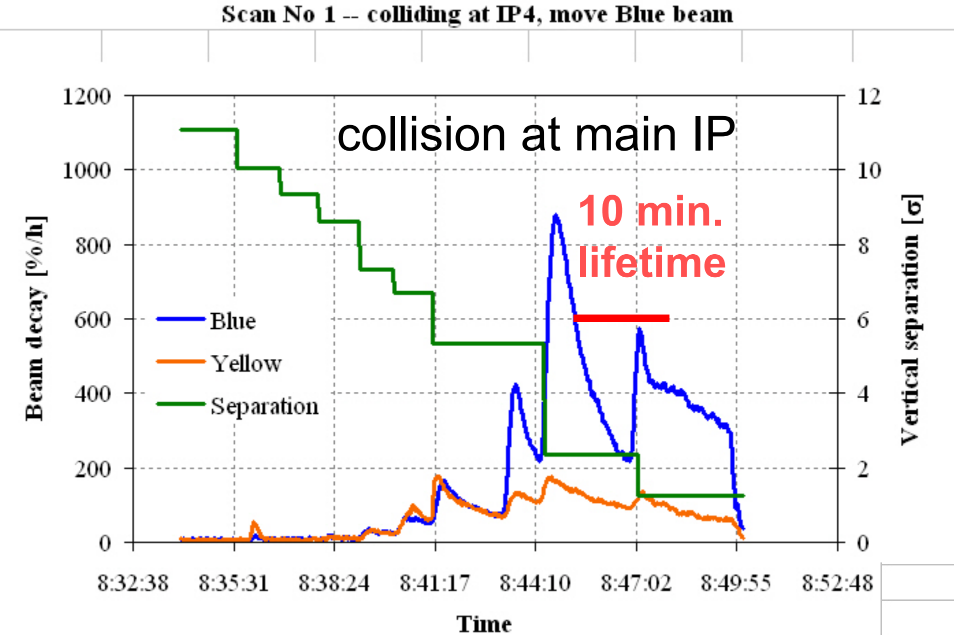
tune scan for PACMAN bunch



dc wire reduces dynamic aperture by ~2σ

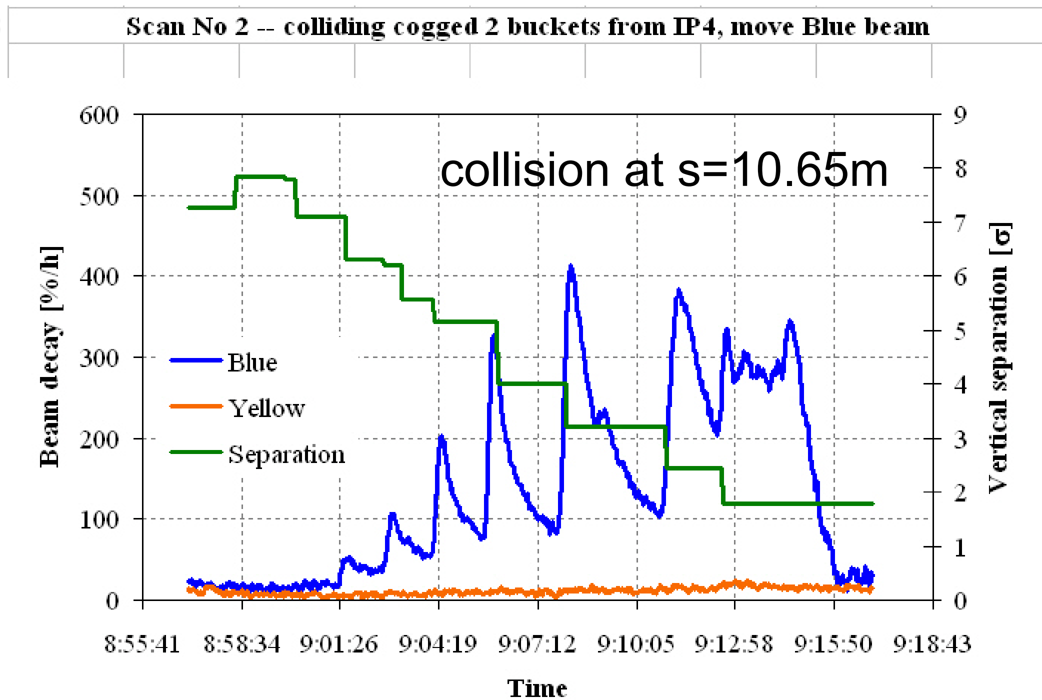
U. Dorda, BBTrack

Long-Range BB Experiment in RHIC, 28 April 2005, Wolfram Fischer, et al., 1 Bunch per Ring

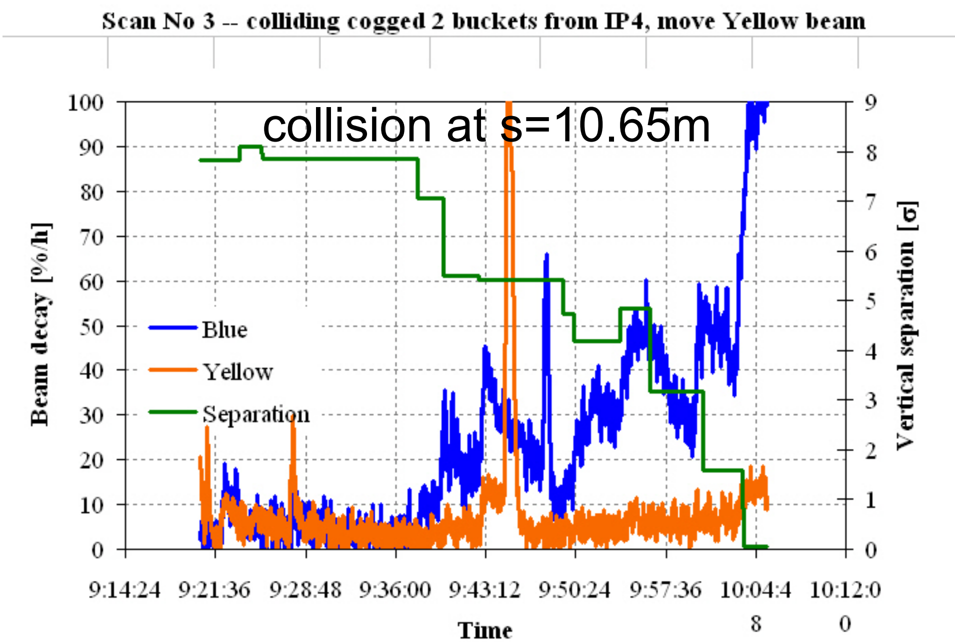


Beam lifetime vs transverse separation - Initial test to evaluate the effect in RHIC.

(1) Experiment shows a measurable effect.
(2) The beam loss is very sensitive to working point.

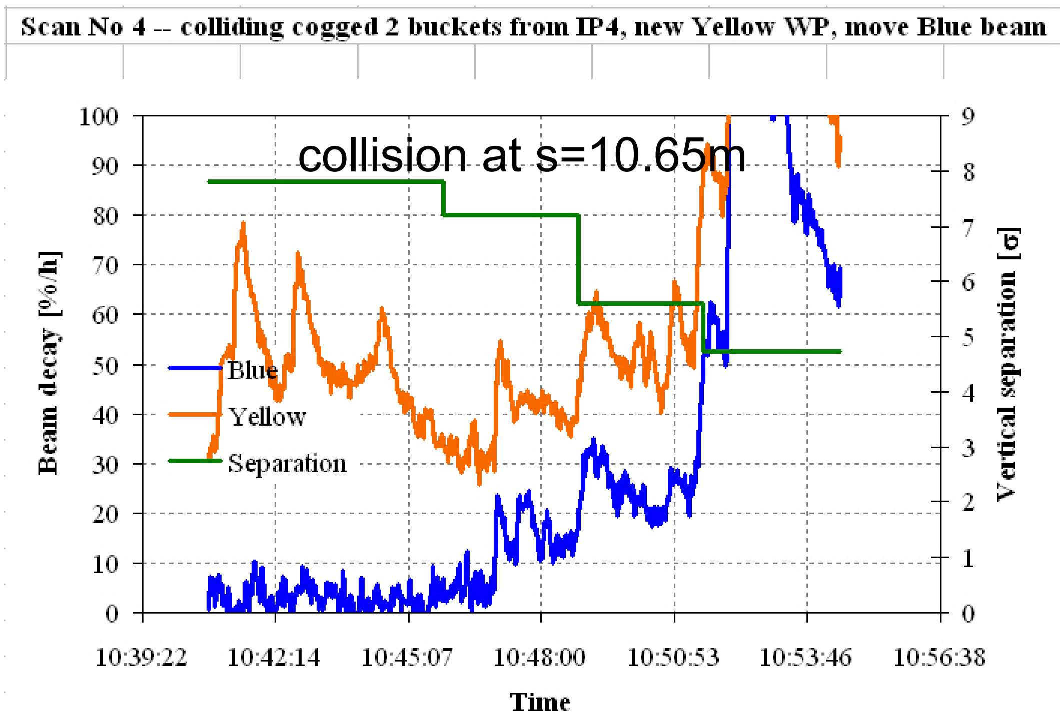


Long-Range BB Experiment in RHIC, 28 April 2005, Wolfram Fischer et al., 1 Bunch per Ring



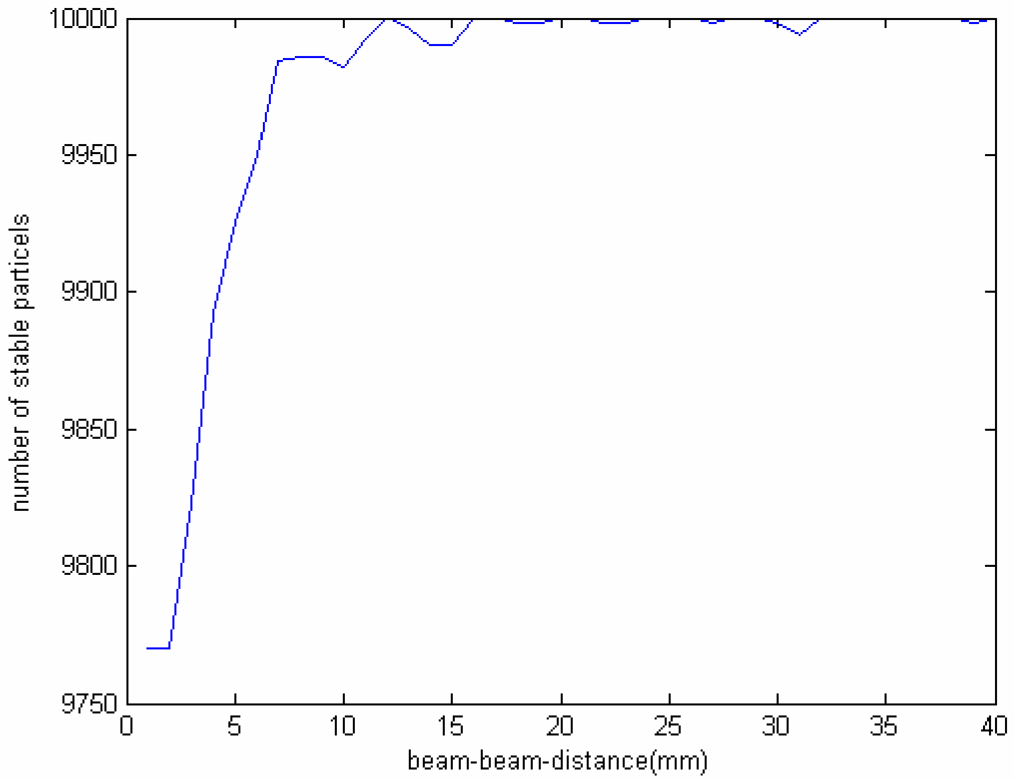
… more data sets

Some time stamps have to be adjusted (used time of orbit measurement, not orbit change); parameters other than the orbit were changed - not shown. ***Scan 4 is the most relevant one.***



RHIC Simulation by Ulrich Dorda

http://ab-abp-bbtrack.web.cern.ch/ab-abp-bbtrack/rhic/rhic-simulations/rhic-simulations.htm



US LHC Accelerator Research Program Task Sheet

Task Name: **Wire compensation of beam-beam interactions**

Date: 23 May 2005

Responsible person (overall lead, lead at other labs):

Tanaji Sen (FNAL, lead), Wolfram Fischer (BNL)

Statement of work for FY06:

- Design and construct a wire compensator (either at BNL or FNAL)
- Install wire compensator on a movable stand in one of the RHIC rings
- Theoretical studies (analysis and simulations) to test the compensation and robustness
- Beam studies in RHIC with 1 bunch / beam at flat top & 1 parasitic interaction.
- Observations of lifetimes, losses, emittances, tunes, orbits for each b-b separation.
- Beam studies to test tolerances on: beam-wire separation w.r.t. b-b separation, wire current accuracy, current ripple

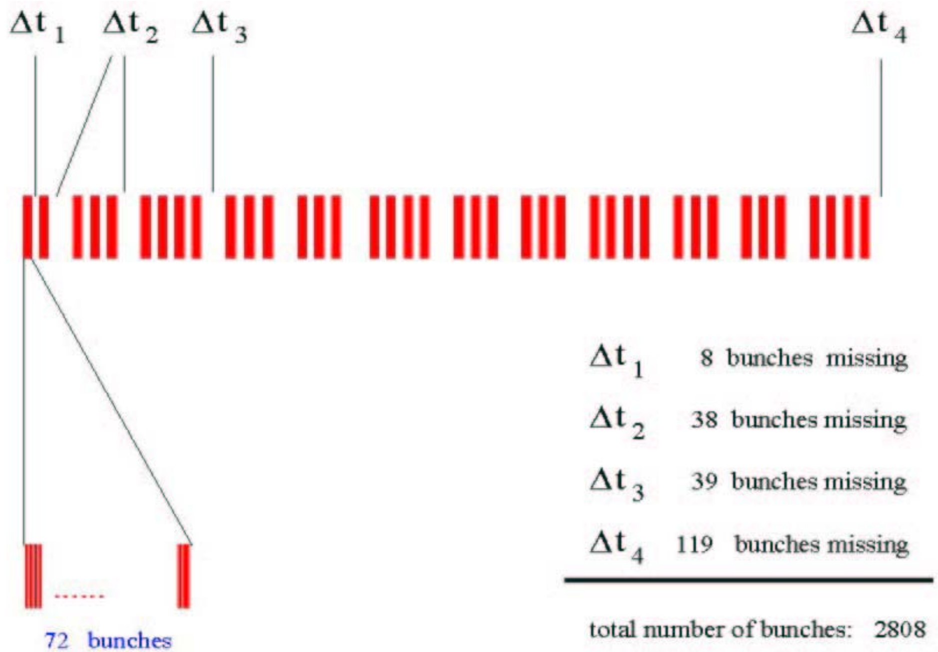
Statement of work for FY07:

- Beam studies with elliptical beams at the parasitic interaction, aspect ratio close to that of the beams in the LHC IR quadrupoles
- Compensation of multiple bunches in RHIC with pulsed wire current. Requires additional voltage modulator

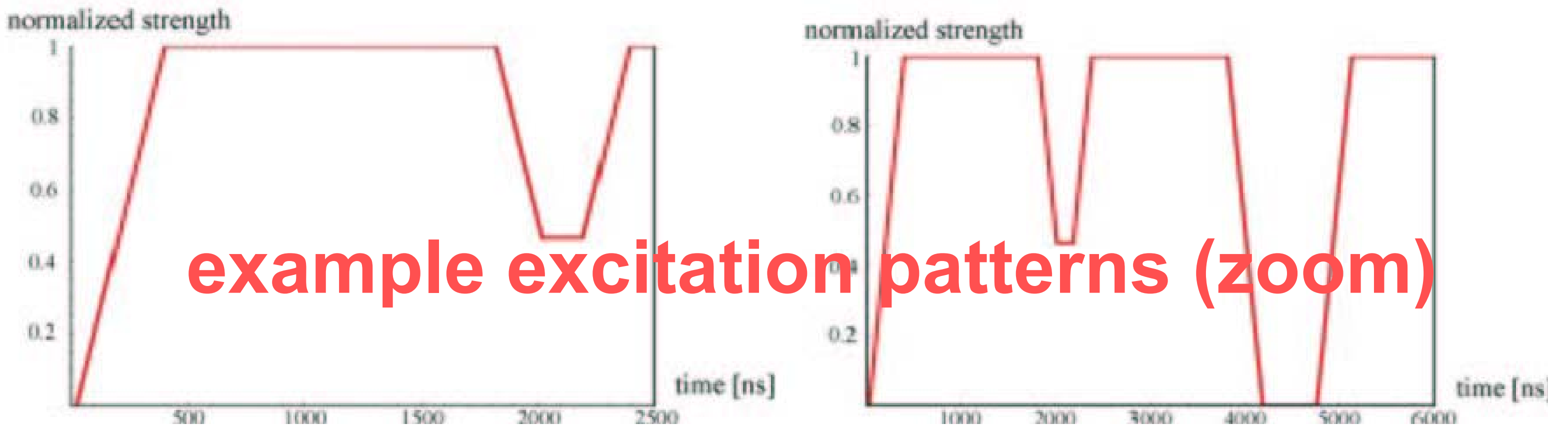
CERN Contacts

J.P. Koutchouk, F. Zimmermann

not to degrade lifetime for the PACMAN bunches, the **wire should be pulsed train by train**



LHC bunch filling pattern



example excitation patterns (zoom)

specifications for pulsed wire compensator

	LHC		SPS (26 GeV/c)	
revolution period T_{rev} (=pattern repetition frequency)	88.9 μs+/-0.0002 μs (variation with beam energy is indicated)		23.5 μs+/-0.02 μs (variation with beam energy is indicated)	
maximum strength	120 Am		120 Am	72 Am
maximum current (smaller currents will also be needed)	120 A (1m)	60 A (2m)	100 A	60 A
0->max ramp up/down time	374.25 ns		374.50 ns	
length of max. excitation	1422.15 ns		1423.12 ns	
lengths of min. excitation (larger min. times may be needed too)	573.85 ns & 598.8 ns		574.24 ns & 599.21 ns	
length of abort gap (could vary)	2594.75 ns		1398.17 ns	
number of pulses per cycle	39		3 (4) or **10**	
average pulse rate	**439 kHz**		130 (173) or **433 kHz**	
pulse accuracy with respect to ideal	5%		5%	
turn-to-turn amplitude stability (rel.)	10^{-4}		10^{-4}	
turn-to-turn timing stability	0.04 ns		0.04 ns	

high repetition rate & turn-to-turn stability tolerance

Conclusions

- **For the nominal LHC, the LR compensation can help tackling with a tight aperture budget. It would push the unstable motion beyond the collimator aperture. It would allow a beam current increase in the nominal insertion. Could open a flat beam option.**

- **For the LHC upgrade, the LR compensation reduces the impact of the geometrical luminosity factor in possibly the cheapest way. It decreases significantly the demand on quad aperture. It decouples the beam current upgrade from the insertion optics.**

- **The experiments in the SPS and the simulations of a dc system give a globally consistent picture showing the success of the compensation principle.**

- **A demonstration of a real compensation is obviously necessary to give full confidence (US/LARP).**

- **With a dc system there is an issue with the Pacman bunches whose stability is reduced. Ways of unfolding the footprint should be investigated.**

- **A pulsed system would be ideal for the Pacman bunches. Its stability is a real challenge. Studies are needed.**